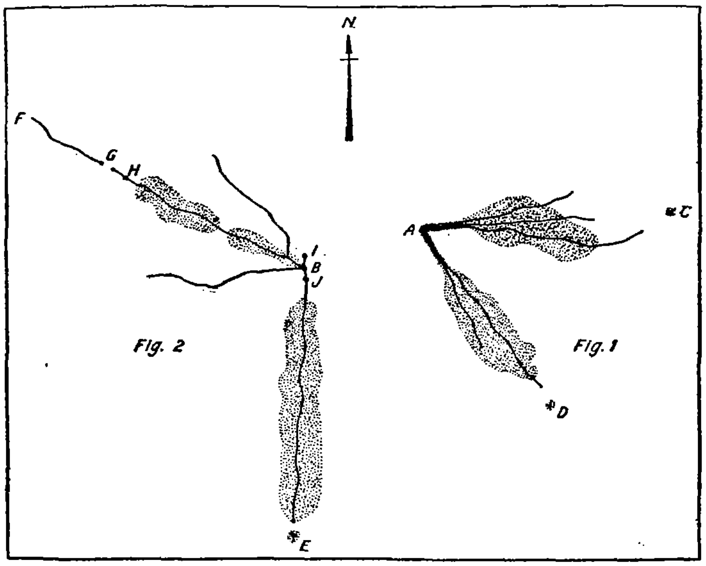
GROUND MARKINGS BY LIGHTNING

By F. F. PAYNE[1]

[Totonto Golf Club, Long Branch, Ontario, Canada, July 14, 1928]

On June 23, 1928, during an electric storm, and while several men were taking shelter in a shed, a green on the course of the Toronto Golf Club was struck by lightning. The grass being exceedingly short, the markings left afforded a unique opportunity for study and measurement. The distance from the shed to the green is 100 yards. The flash was described as blinding and the thunder as deafening. Immediately after the flash, smoke and



steam were seen rising from the green, and upon examinarion it was found littered with a small quantity of earth and grass roots. These came from some deep holes and grooves, and the grass at the edge of these was slightly burned. Elsewhere the wet grass was only withered by heated moisture. Definite lines forming angles soon appeared, these lines being indicated by continuous withered grass. Upon each side of the main lines or legs of the angles there were also wide patches of withered grass along the greater part of their length. In the case of some less definite lines the side grass was uninjured. It is evident that the markings shown in Figures 1 and 2 were caused by the same flash but the grass between *A* and *B* was untouched. Possibly the flash divided when near the ground. At *A* was a deep, round hole and for a short distance lines diverging from it were wide and deep, while at *B* the earth was showing but the scoring was not deep and a hole immediately at this point was not visible. There were small holes, however, north and south of this point 3 inches apart, slanting northward and southward, respectively.

The main legs or lines were more or less scored, showing earth as though a small bullet had ricocheted along these lines, while other lines showed only withered grass.

The most remarkable discovery was that of short round tunnels at the end of the lines at *C*, *D*, and *E*, also a short distance up the line, *B* to *F* at *G*. The course of the current was evidently outward as the entrance holes of these tunnels were slightly cut, while the escaping holes were covered with dead grass and were only discovered by passing a pliable stick through the tunnels. The grass above all these tunnels remained green. At *H* (Fig. 2) there was a deep, narrow hole sloping slightly toward the northwest.

After careful examination the impression left was that upon striking the ground at *A* and *B* the fluid had splashed and bounded outward down the lines shown in the diagram.

The following measurements are appended:

Upper short groove at *A*, 6½ inches long, ⅞ inch wide.
Lower short groove at *A*, 7 inches long, ⅞ inch wide.
Width of tunnels at entrance, ¼ inch.
Length of tunnels at *C*, 12½ inches; at *D*, 4 inches; at *E*, 3½ inches; at *G*, 3 inches.
Extreme depth of tunnels, 1 inch.
Length of lines, *A* to *C*, 44 inches; *A* to *D*, 39 inches; *B* to *F*, 61 inches; *B* to *E*, 40½ inches.
Distance of small hole at *H* from apex at *B*, 38 inches.
Hole at *A*, ¾ inch in diameter and 5 inches in depth.
Depth of hole at *H*, 4 inches; diameter, ¼ inch.
Depth of hole at I, 4 inches; diameter, ¼ inch.
Depth of hole at *J*, 3 inches; diameter, ¼ inch.
Distance from *A* to *B*, 43 inches.
Distance from *A* to bamboo flagpole, 15 feet.
Distance from *A* to nearest tree, 150 feet.

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FRANKLIN'S KITE EXPERIMENT AND THE ENERGY OF LIGHTNING

By ALEXANDER MCADIE

(Blue Hill Observatory, Mass.)

SYNOPSIS

Franklin's kite experiment as described by him in the well-known letter to Collinson, dated October 19, 1752, naturally challenged the attention of the scientific world and established the electrical nature of lightning. Efforts to get accurate dates and details have proved unavailing thus far, although it would seem that in contemporaneous journals and correspondence some corroborative evidence must exist.

The common belief that the kite experiment paved the way for the introduction of the lightning rod is disproved by Franklin's own use of the rod and his clearly expressed views as to the identity of lightning and electricity, at earlier dates.

Perhaps the most promising method of obtaining knowledge of the nature of lightning is the duplication by artificial means of high voltage discharges having considerable current and very steep wave fronts. Such work is now carried on by the General Electric Co. in its high tension laboratory at Pittsfield, Mass., under the direction of Mr. F. W. Peek, jr. These discharges may well be called *near-lightning*, and illustrate well the peculiar characteristics of the natural discharges whether we regard them as oscillatory or unidirectional.

There has been a tendency in scientific circles to depreciate the importance of this line of attack and to give preference to values obtained on theoretical grounds and measurements which seem open to criticism. Attention is called to an error in a published statement critical of our estimate of the energy of an average flash; and it is shown that confusion has arisen from the use of units with similar initials but quite different values.

Some approximate measurements of the energy in kilowatt-hours are given, based upon fusion of kite wire at Blue Hill Observatory, and the voltage is shown to be of the order of 13,000,000 as compared with 10,000,000,000 given by so eminent an authority as C. T. R. Wilson. Kite experiences at a number of Weather Bureau stations are summarized as confirmatory of the lower values.

The importance of a study of the side discharges or split-off flashes is urged as contributing to a knowledge of the process of breakdown of the dielectric, the origin of the path, the concentration of electrons producing ionization, and the nature of the explosive effect.

In a short letter to C. C. Esq (Cadwalader Colden?) dated 1751 without month or day, Benjamin Franklin tells of possessing five bottles (Leyden jars) containing 8 or 9 gallons each; two of which when electrically charged were sufficient for all his experiments. He concludes with "bottle may be added to bottle ad infinitum and all united and discharged as one." Then follows a characteristic Franklin deduction: "The greatest known effects of common lightning may without much difficulty be exceeded in this way." He overlooked the limits of insulation.

As early as November, 1749, he had come to the conclusion that since the effects of lightning and the electricity of static machines (frictional glass and sulphur globes) and Leyden jar discharges were similar in so many ways, then lightning must be electrical in character. His "Opinions and conjectures, based on experiments made in Philadelphia in 1749," and his "Observations and suppositions toward forming a new hypothesis for explaining the several phenomena of thunder gusts" (1749) were transmitted to Europe, chiefly through Peter Collinson, Esq., F. R. S., London, and attracted much attention.

In September, 1752, Franklin erected on his own house an iron rod. The exact date of the kite experiment we have not been able to ascertain, although many authorities on Frankliniana have been consulted and search made of collections in Philadelphia, Boston, and Worcester. In Franklin's own newspaper, the Pennsylvania Gazette, there is no mention of any kite experiment until late in October, under date of October 19, 1752, when there was published the well-known letter which begins with a reference to "frequent mention in public papers from Europe of the success of the Philadelphia experiment for drawing the electric fire from clouds by means of a pointed rod of iron erected on high buildings, etc."

He goes on to say that "the same experiment has succeeded in Philadelphia though made in a different and more easy manner"; and then follow directions for making a kite and a description of what will happen when the kite is raised during a thunder gust. There are three known copies of this letter. No specific date is mentioned in any of them, which is strange, for in his cloud experiments Franklin noted not only date and place but also the hour. In the copy which my predecessor, the late Prof. Lawrence Rotch, purchased are the words "anyone may try," words which are not in the letter published in the Philadelphia Transactions, 1752, page 565, and dated October 1, 1752. Nor is it stated explicitly in any of the letters that the experiment was actually made. A final paragraph in the Transactions letter, not found in the others, reads:

> I was pleased to hear of the success of my experiments in France and that they there begin to erect points upon their buildings. We had before placed them upon our academy and statehouse spires.

From what precedes we infer that the rod antedated the kite. Accounts in most textbooks lead one to believe that the kite experiment led to the invention and adoption of the rod.

There is nothing in the correspondence between Franklin and Kennersley in the first half of 1752 that hints at any kite experiment; and as their relations were friendly and Kennersley had loaned Franklin a brimstone globe it is puzzling to understand why so crucial an experiment was not mentioned. It is true that Franklin in his autobiography says that the kite was flown in 1752, but this was written when he was an old man, largely from memory; and it seems to us that he may have confused his experiments made on the electrical nature of clouds in 1753 with the kite experiment. The date given in the Britannica, June, 1752, is probably erroneous, a confusion with June 6, 1753, when between 5 and 7 p. m. Franklin watched a cork ball swing to and fro between two jars, one electrified by the insulated rod (or accumulator of the air potential) and the other charged by his frictional machine. An interesting deduction based upon these experiments of 1753 was:

> So that for the most part in thunder strokes it is the earth that strikes into the clouds and not the clouds that strike into the earth.

One may compare this with our latest views on the mechanism of a thunderstorm (Dr. G. C. Simpson, Proc. Roy. Soc. vol. 114, 1927, p. 380), where it is shown that lightning "can not start at a negatively charged cloud" and therefore "any discharge between the ground and this [negatively charged] part of the cloud must start on the ground and branch upward." Furthermore, in another paper from an examination of 442 photographs Simpson shows that the "preponderance of the lower clouds from which lightning discharges proceed are positively charged." (Proc. Roy. Soc. A vol. 111, 1926, p. 67.)

As stated above, the rod experiment of drawing or extracting electricity from the atmosphere during thunderstorms aroused great interest in Europe. In London the summer of 1752 was cool and damp and only one thunderstorm, that of July 20, afforded opportunity to test the hypothesis. Watson obtained no sparks; but Canton, Bevis, and Wilson succeeded. The experiments in France were more successful, and it was as an amplification of these that the kite letter was written and made public. So far as we can at present determine, the first individual to observe a spark from an insulated conductor during a thunderstorm was the old soldier Coiffier on guard Wednesday May 10, 1752, about 2:20 p. m. at Marley. The story was told by M. D'Alibard to the Academy of Science at Paris, May 13.[1]

It is a far cry from Marly, 1752, to Pittsfield, Mass., 1928; from the small spark due to an induced charge on an insulated conductor to the near-lightning discharges obtained by Mr. F. W. Peek, jr., of the General Electric Co., illustrated herewith. (Fig. 1.) Figure 2 is a photograph of a natural lightning flash made by A. H. Binden. When Franklin used the electrified rod, the difference of potential between the point and the earth probably did not exceed 5,000 volts even at the maximum just before the flash occurred. In the case of the artificial flash the potential difference is 3,600,000 volts. We may estimate this as about one-third the voltage of an average lightning discharge 300 meters in length. In preliminary experiments Peek found for a meter spark a voltage of about 330,000 volts; but as will appear later, there is no assurance that multiplying this value by length will give a true value for a natural discharge.

Briefly, the Pittsfield experiments are the outcome of studies made for the protection of high-voltage transmission lines. Peek has measured lightning voltages on such lines in a mountainous region (Colorado) and found

[1] Je suis allé chez Coiffier qui déja m'avoit dépêché un enfant que j'ai rencontré en chemin pour me prier de venir; j'ai doublé le pas à travers un torrent de grêle. Arrivé a l'endroit ou est placée la tringle coudée, j'ai présenté le fil d'archal, en avançant successivement vers la triangle, à un pouce et demi ou environ; il est forti de laeringle une petite colonne de fer bleuâre sentant le soufre, qui venoit frapper avec une extrême vivacité le tenon du fil etc. etc. (Extrait d'un Memoire de M. D'Alibard.)

line potentials as high as 500,000 volts, while insulator flashovers by lightning have occasionally indicated voltages as high as 1,500,000 or more. In various papers read before electrical engineering societies Peek has given full descriptions and details of the apparatus used. (See High Voltage Phenomena, Journal of Franklin Institute, January, 1924, September, 1924, November, 1925, and Smithsonian Report, 1925, p. 169–198.) Large wooden posts can be split by this near-lightning; and in fact the phenomena of lightning can be duplicated on a scale, not greatly reduced from that of the natural results. By the use of models representing cloud capacities and transmission lines, Peek found that when a flash occurred 1 per cent of the model cloud's voltage was induced on the model line.

The induced voltage being determined, the indicated voltage of the lightning was found to average about 100,000,000 volts. He states that the lightning voltage during a storm will of course vary over a very wide range, sometimes much higher, but generally lower than the value above. It has been observed that during a severe thunderstorm there may be many induced strokes at very low voltages, a less number at moderate voltages and so on to the very few at the extreme voltages. These values indicate a gradient of 330 kv/m in the most dense part of the electric field where the flash occurs, and a gradient of less than 100 kv/m at a distance of 500 meters. The current is of the order of 80,000 amperes and the energy 13,500 kilowatt-seconds or 3.8 kilowatt-hours. To express this in homely terms, the energy of an average flash would be sufficient to operate an automobile about 5 miles or an electric toaster for a day. The time of dissipation of the energy is all important and this will also determine the explosive and destructive effects.

We can not here give details of construction and measurements. Most lightning flashes are impulse discharges, having steep wave fronts. Assuming a height of 300 meters, a cloud area of 10,000 square meters, and an ohmic resistance of 1,000 ohms the capacity will be approximately 25 by 10^{-7} millifarads and the inductance 0.0005 henry. The time may range from .01 second to .000001 second. In most cases lightning is well described as an explosive effect of electrical energy. An exceedingly small time will give for the power involved something like 100,000 kilowatts.

The values given by Peek have been criticized by Dr. G. C. Simpson as much too low for an average flash. Possibly flashes are longer in Great Britain than in the United States, and perhaps the cloud areas are larger. On the one hand we have Peek's values of 6 coulombs (or 18 by 10^9 E. S. U.) while Simpson upholding Wilson's estimates makes the values about seven hundred times larger. Thus the energy of an average British flash would be about 3,000 kilowatt-hours. In homely figures as given by Simpson (Meteor. Mag. July 1927, p. 135):

> One lightning flash an hour on Professor Wilson's estimate would produce all the electrical power required by a modern industrial city of 100,000 inhabitants, 24,000,000 British thermal units. Thus a large generating station is more suitable for comparison with a thunderstorm than an electric toaster.

A mistake was made in printing British thermal units when British trade units were meant. Twenty-four million thermal units would be only 7,034 kilowatt-hours; whereas trade units would be 24,000,000 kilowatt-hours. Incidentally our electrical engineers tell me that this estimate is much larger than is found in their practice.

It is difficult to determine just what the concentration of charge is at the point of discharge at the given microsecond. Again, the polarity of the cloud as a whole must be considered, as one portion may be positive and elsewhere negative. Thus T. W. Wormell (Proc. Roy. Soc. A. vol. 115, 1927, p. 455) holds that while in most cases the thundercloud is of positive polarity there can be such a distribution of electric field as to indicate that the cumulo-nimbus is often bipolar; that is, upper portion positive, lower portion negative. Schonland and Craib (Proc. Roy. Soc. vol. 114, 1927) state that of 18 thunderstorms studied by them only 1 was of negative polarity. Sudden changes of field due to distant lightning were predominantly negative and those due to near discharges predominantly positive. Their results indicate that thunderclouds are bipolar, upper pole positive and lower pole negative. Their mean value for 82 lightning discharges was 94 coulomb kilometers which they consider as satisfactory in magnitude with the 148 coulomb kilometers found by Wilson.

Doctor Simpson in a letter to the writer doubts if a flash ever starts at a less height than 3 kilometers. This seems to us more like a maximum than average value. Wilson's values are determined by integrating the volume charges before and after the flash but the method is open to objection inasmuch as the changes are incessant and their relations can not be differentiated. The field values may even undergo reversal within short distances.

Doctor Simpson points out that values of potential gradient made at the ground can not indicate true flash energy since they give no evidence as to field strength. He holds that the discharge produces its own field as the channel along the discharge passes bores its way through the air. Probably he is right; but this would lower the required voltage.

As a partial and no doubt very imperfect contribution to the subject, I have gathered together a number of cases where kite wires have been struck by lightning. At Blue Hill we have tried to fly kites during light thunderstorms; but the practice is dangerous and for self-evident reasons experiments have not yet been carried as far as they might be under different conditions. At other places kite wires have been struck and the following abbreviated list may serve as illustrative of ground phenomena at such times.

1. Blue Hill: Lower kite 700 meters high; kite wire out 1,600 meters. About 600 meters fused. Weight 3,600 grams. Energy of fusion at 1,800 calories per gram equals 6.48 by 10^6, or 7.5 kilowatt-hours. We estimate the current strength as 27,112,320 watt-seconds, and with a time of 0.001 second and resistance 700 ohms, the current would be 6,224 amperes and the voltage would be 1,400,000. On the other hand, a short time like 0.0001 second would indicate a voltage of 13,000,000 and energy 25 by 10^6 kilovolt-amperes. Even under such conditions the voltage is less than the 10^9 given by Wilson; and the coulombs 6 as against 50 or 100.
2. Ellendale: Six kites and 6,500 meters of wire out; 3,000 reeled in as the thundercloud approaches. Lightning strikes and the wire is not fused but discolored and distempered.
3. Royal Center: 1,300 meters of wire vaporized. Convection vigorous enough to cause thunderstorms only below 2,800 meters.
4. Ellendale: 2,200 meters of wire out. Upper section between second and third kites struck; wire blackened and distempered and splice joints melted.

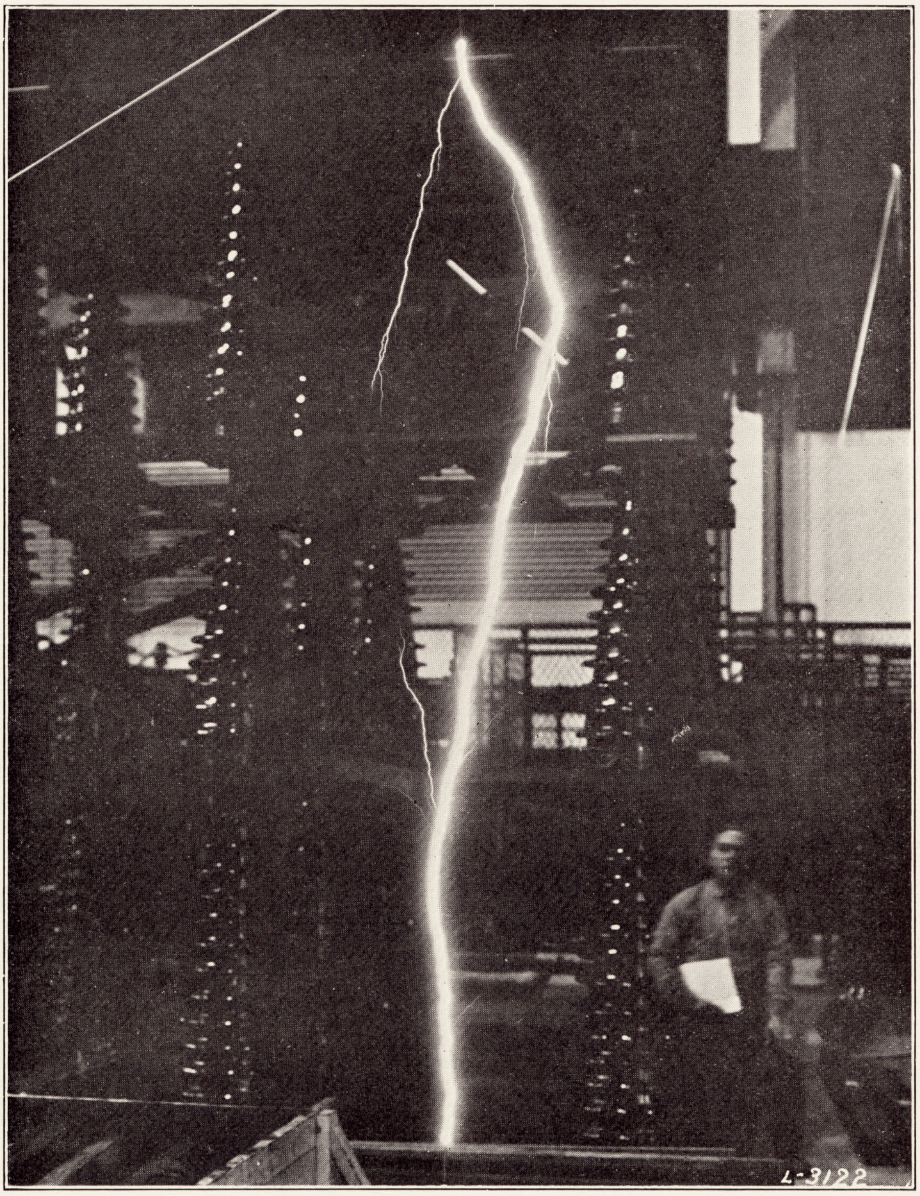

FIG. 1.—Near-lightning flash, 3,600,000 volts. F. W. Peek, General Electric Co.

FIG. 2.—Natural lightning flash photographed by A. H. Binden

5. Drexel: Voltmeter showed in excess 50,000 volts for altitude 1,600 meters. Steady stream of brilliant sparks jumping 10 centimeters. Thunder first heard at 8.33 a. m. At 9.23 flash of lightning and thunder; 4,000 meters of wire out. Effect on wire as follows:

Length from head kite (meters)	Diameter of wire (millimeters)	Condition
0 to 800	0.9	Destroyed.
800 to 1,600	1.0	Brittle like glass.
1,600 to 1,900	1.0	Dark blue.
1,900 to 2,075	1.0	Yellowish brown and dark blue.
2,075 to 2,260	1.0	Very dark blue.
2,260 to 3,600	1.0	Apparently not affected.
3,600 to 3,680	1.1	Light brown.
3,680 to 3,800	1.1¼	Dark brown.
3,800 to 4,000	1.1¼	Dark brown to dark blue.

The string attaching head kite to wire was burned. That portion of the wire within the lower stratus cloud (below 1,000 meters) showed no ill effects from lightning, whereas that portion between base of cloud and earth (650 meters) was considerably affected in spite of the fact that it was wire of larger diameter, and therefore less resistance. The wire in the dry air (2,300 to 1,300 meters) between the two clouds layers was either entirely destroyed or rendered unfit for use. It is evident that the electric charge originated in the upper cloud layer and much of it passed along the wire into the lower cloud. A portion continued to earth but did not affect the wire because of the moisture on it, but did injure the wire in the drier air below. Thus an airplane might form part of the path of discharge. (See Supplement No. 10, M. W. R., 1918, pp. 5-6.)

6. Broken Arrow: 1,800 meters out; three kites. Stratus cloud 400 meters high. Lightning strikes head kite and completely destroys wire from kite to reel house leaving along the path a discharge a streak of thick yellowish brown smoke. If this discharge occurred in 0.001 second, the voltage is not far from 3,000,000, or about that of the artificial near lightning of Peek. Compare this with the next case.

7. Drexel: 3,535 meters of wire, except 20 or 30 near the reel, vaporized. The lower portion fused.

8. While not a kite wire record, it may be mentioned that on April 16, 1926, an airplane carrying eight passengers going from Paris to London was struck near Beauvais. A large patch of fabric was torn out. the compass demagnetized, one of the main spars scorched, all bondings fused, and one aileron badly damaged.

Doctor Dorsey has advanced the theory that there are electronic darts, or localized stream lines of electrons and that a positive stroke advances by a series of steps depending upon the occurrence of free electrons. Branching is to be expected; while in a negative stroke the electrons advance in a mighty rush. He objects to Doctor Simpson's deductions from the preponderance of negative polarity in side-split branches, as shown in many photographs. Inspection of the 3,600,000 volt flash herewith shows, curiously enough, split-off discharges in both directions from the same flash.

Humphreys has calculated (Physics of the Air, p. 396) in the case of a hollow tubular conductor crushed by lightning and assuming certain temperatures, an amperage ranging from 19,470 to a maximum of 100,000. With the latter value and assuming a megadyne pressure on the inner tube, there results a pressure of 2,638 by 10^4 dynes per square centimeter or roughly 26 atmospheres. He warns, however, that these are rough estimates and "that this particular discharge presumably was exceptionally heavy since it produced an exceptional effect." He also quotes Pockels estimate of 10,000 amperes. Mr. S. A. Korff, of the General Electric Co., has called my attention to Steinmetz's estimate of the energy as 10^1 watt-seconds or 2.8 kilowatt-hours which is only a thousandth of Wilson's value. Larmor has estimated the energy as 28 kilowatt hours. (Proc. Roy. Soc. 1924, Vol. 90, p. 312.) Since the voltage breakdown of air is 9 by 10^9 volts it seems likely that estimates exceeding this are too high; and as the breakdown is probably progressive, values of 1.2 by 10^7 volts are ample, thus bringing the energy value to approximately 28 kilowatt-hours.

For the benefit of the lay reader then we may say that in our opinion the energy of an average flash of lightning does not run much over 10 kilowatt-hours or, let us say, enough to operate three ordinary toasters (300 watts) for 10 hours.

PHENOMENA PRECEDING LIGHTNING

By ALEXANDER MCADIE

(Blue Hill Observatory, Mass.)

In the Meteorological Magazine June, 1928, p. 113, Mr. R. S. Breton, writing from Tung Sung, Southern Siam, states that on a number of occasions he has noticed a sharp "vit" or "click" accompanying lightning that has struck something in the immediate neighborhood, preceding the thunder by a perceptible fraction of a second.

He adds that he has three times noticed that animals show alarm immediately before a flash and that in one case a dog walking on grass turned and began to bark angrily in the direction of a very strong flash that came one-fourth second after, striking several of a group of trees 200 yards away. He mentions two occasions when fowls rushed for shelter from the open in alarm before a very near discharge actually took place. In each case the discharge was a very powerful one, taking place on dry soil before rain had fallen. He asks "if it may be that the sensitive feet of the dog could detect vibrations before the discharge took place."

The editors of the magazine answer "that the 'vit' or 'click' accompanying lightning which has struck close by appears to be new; no reference to any similar observation can be found in the literature and at present it is not possible to offer any explanation."

Clicks preceding intense lightning flashes are common at Blue Hill Observatory and undoubtedly can be heard elsewhere under certain conditions, when an insulated metallic conductor is exposed, in a strong electric field, and a grounded conductor is close by. At Blue Hill every intense flash within a radius of 1,000 meters gives this click preceding thunder by an interval which is a function of the distance of the flash. Thus for an interval of 0.4 second (a frequent value), with mean temperature of air column from ground to cloud 1,100 kilograds (303° A. or 86° F.) relative humidity 90 per cent absolute humidity 27 grams per cubic meter of space, wind direction 235° (SW. by S.) velocity 7 meters per second, the distance is

$$\begin{aligned} d &= t\ (V_0 \sqrt{T/1000}) + \text{wind} \\ &= 0.4\ (332.11 \times 1.05) \times 7 \\ &= 142 \text{ meters} \end{aligned}$$

Intervals as large as six seconds indicating a flash distant 2 kilometers or more have been noted.

Regarding the behavior of the dog, it would seem to be not so much a question of sensitive feet as a matter of insulation and increasing electrification to a degree that the hairs, for instance, become discharging points. This bristling can be seen readily on animals caught in thunderstorms near the top of a mountain. I recall being near the summit of Mount Whitney (4,420 meters above sea level, 14,502 feet), during a thunderstorm. The hairs of the burros (pack animals) stood out straight,